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ULTRA LIGHT-WEIGHT FLAT PLATE SOLAR COLLECTOR PERFORMANCE CHARACTERIZATION

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ABSTRACT

Experimental testing was carried out on Asecor's "Ultra Light-Weight Flat Plate Solar Collector" prototype to determine its thermal performance and flexural rigidity. The thermal performance was evaluated at two tilt angles: 60° and 78° The tests indicated an effective $F_R \cdot \tau\alpha$ of approximately 0.72, and an effective F_R-U_L of approximately 9.75 W/m²-C. The collector's flexural rigidity was evaluated by measuring the deflection of the collector under known loads. The product EI was estimated to be 17,255 Nm² based on the deflections measured with the collector simply supported. Several suggestions are offered for increasing the rigidity of the collector.

Performance simulations were run to obtain economic data to be used to evaluate the market potential of the collector. As a domestic water heater operating in Ottawa, it is expected to deliver energy at about $12.36/GJ, whereas it could deliver energy for swimming pool heating at about $4./GJ.

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EXECUTIVE SUMMARY

There were two main objectives of this work, namely to:

a) Perform thermal and mechanical tests on the ultra light-weight solar collector prototype, and

b) Appraise the market potential of this collector, based on performance and cost.

The thermal performance was evaluated at two tilt angles: 60° and 7[illegible]° The tests showed efficiencies of over 50% for temperature differentials between the fluid and surroundings of less than 27°C, with an effective $F_R \cdot \tau\alpha$ of approximately 0.72, and an effective F_R-U_L of approximately 9.75 W/m^2-C.

The collector's flexural rigidity was evaluated by measuring the deflection of the collector under known loads, using two methods of supporting the collector, simply supported and a partially clamped support. The product EI was estimated to be 17,255 Nm^2 based on the simply supported measurements, whereas EI was deduced to be only 3,600 Nm^2 in the tests which assumed the collector to be rigidly clamped at two beam positions. Deflections of up to 8 mm were measured for the simply supported collector set-up, whereas a deflection of 2mm was measured for the arrangement in which the collector was 'clamped' to its support, for the same load distribution as used for the simply supported tests. Clearly, on the basis of deflection, the clamping increased its rigidity, but on the basis of the deduced EI product, not as much as it should have if it was exactly clamped at the supports.

On the basis of the results of this study, it is believed that improvements can be realized in the collector's thermal performance, rigidity (strength) and cost of production. Improvements to thermal efficiency may be realized by using narrower fins in the 'Sunstrip' absorber, and better system efficiencies could be experienced if insulated short connector hoses were employed between the various parts of the system. To increase the collector's strength, the back glazing could be replaced with an aluminum sheet riveted to the frame and brackets could be installed at the frame corners. Another method of increasing the collectors flexural rigidity and strength would be to return to the original frame design which was intended in the development of the prototype. The materials cost of producing the collectors could be reduced by replacing the back glazing with an aluminum sheet. If production volume warranted, a rollbonded absorber which allows for trickle flow of the fluid over the entire surface would probably give better performance and be more cost effective. It was not possible to produce such an absorber with the limited budget of this or the previous project, however.

Using the results of the thermal efficiency evaluation,

and a projected cost estimate of $100./m² for the collector units, a simulation was run with a WATSUN package. A life cycle unit cost of $12.36/GJ was projected for its use in a domestic water heating application using weather data for Ottawa. A modified simulation to represent its use as a swimming pool heater suggested that it would provide a life cycle unit cost of about $4./GJ in this application, also in the Ottawa weather conditions. It is therefore expected to have a very favourable reception in a more southerly climate, especially in areas where electrical costs are substantially higher than in Ontario. A market potential of the order of $500,000./year was projected to be an attainable figure for the sale of these collectors only, without including other components of the system.

1.0 Introduction

1.1 Background to the Present Work

Development intended to provide a low-cost, ultra light-weight flat plate solar collector was undertaken by Asecor Ltd., (with IRAP support) in an earlier study.[1] In that study, a great deal of progress was made to meet the original objective, but the prototypes constructed were not tested for thermal performance or for strength. Cost estimates were made for the production of the type of collector developed, in that study, but more needed to be done on a market analysis.

1.2 Objectives of the Present Work

The first objective of this work was to perform thermal and mechanical testing of the ultra light-weight collector prototype built in the earlier work,[1] and to make whatever design changes seem advisable after the testing.

The second objective was to make an appraisal of the potential for this type of collector in the Canadian and world markets.

1.3 Approach Taken

It is recognized that the marketability of a solar collector depends not only on its price, but on a cost/benefit ratio, as well as on its versatility in use. The benefits depend on the thermal performance, and the versatility of its usefulness depends, to some extent at least, on its mechanical strength. Therefore, the mechanical strength and thermal performance of the newly developed solar collector were of primary interest. In this study, the thermal performance was evaluated by experimental testing and through the computation of its efficiency vs. $\Delta T/I$ characteristic. Mechanical strength was investigated by determining the deflection of the collector under various load distributions, with several methods of support.

2.0 Thermal Performance Evaluation

2.1 Experimental Set-Up

Figure 1 shows a schematic drawing of the experimental set-up used to evaluate the thermal performance of the "Ultra Light-Weight Flat Plate Solar Collector". The installation consists of indoor and outdoor sections. At the collector intake and outlet, dial thermometer gauges were used to obtain the temperatures for the purpose of evaluating the average temperature of the collector fluid. The indoor components include an insulated water storage tank with a capacity of 40 gallons (182 liters), a circulating pump, filter, control valves, an electric heater, and thermocouples for temperature measurement. Iron-constantan (type J) thermocouples were used to determine temperature with the help of tables of temperature vs. the thermoelectric voltage reading.

The outdoor portion of the thermal testing set-up consisted mainly of the solar collector stand and the solar collector itself, mounted at a pre-selected tilt angle. Although the tilt angle of the solar collector was intended to be varied between 0 and 90°, it was difficult to increase it beyond 78° without some modification of the collector stand, which was not undertaken in this work. The outdoor components also included an Eppley pyranometer. This was used to measure the total solar irradiation (diffuse and direct) incident upon a horizontal surface per unit time per unit area. The pyranometer was connected to the same voltmeter that measured the thermocouple voltage, so a switch was needed to select between the thermocouple and the pyranometer. The diffuse part of the solar radiation was approximated by measurement with the pyranometer while it was manually shaded from the direct solar radiation component.

The collector was linked to the indoor flow network through 20 mm diameter heater hose which can withstand temperatures of up to 150°C, at the normal operating pressures. It should be noted that the electric heater and the solar collector were not operated simultaneously. The components illustrated in Figure 1 facilitated the choice of the loop for fluid circulation during any particular test.

2.2 Test Procedure

2.2.1 Solar Collector Loop

A fixed amount of water (~ 40 kg) was placed in the storage tank for all testing purposes. This water could be heated in the smaller loop by the electric heater if it was required. The water was circulated through the solar collector by a pump. A vent pipe (air bleeder) was used to maintain the tank pressure at the atmospheric value during the entire test.

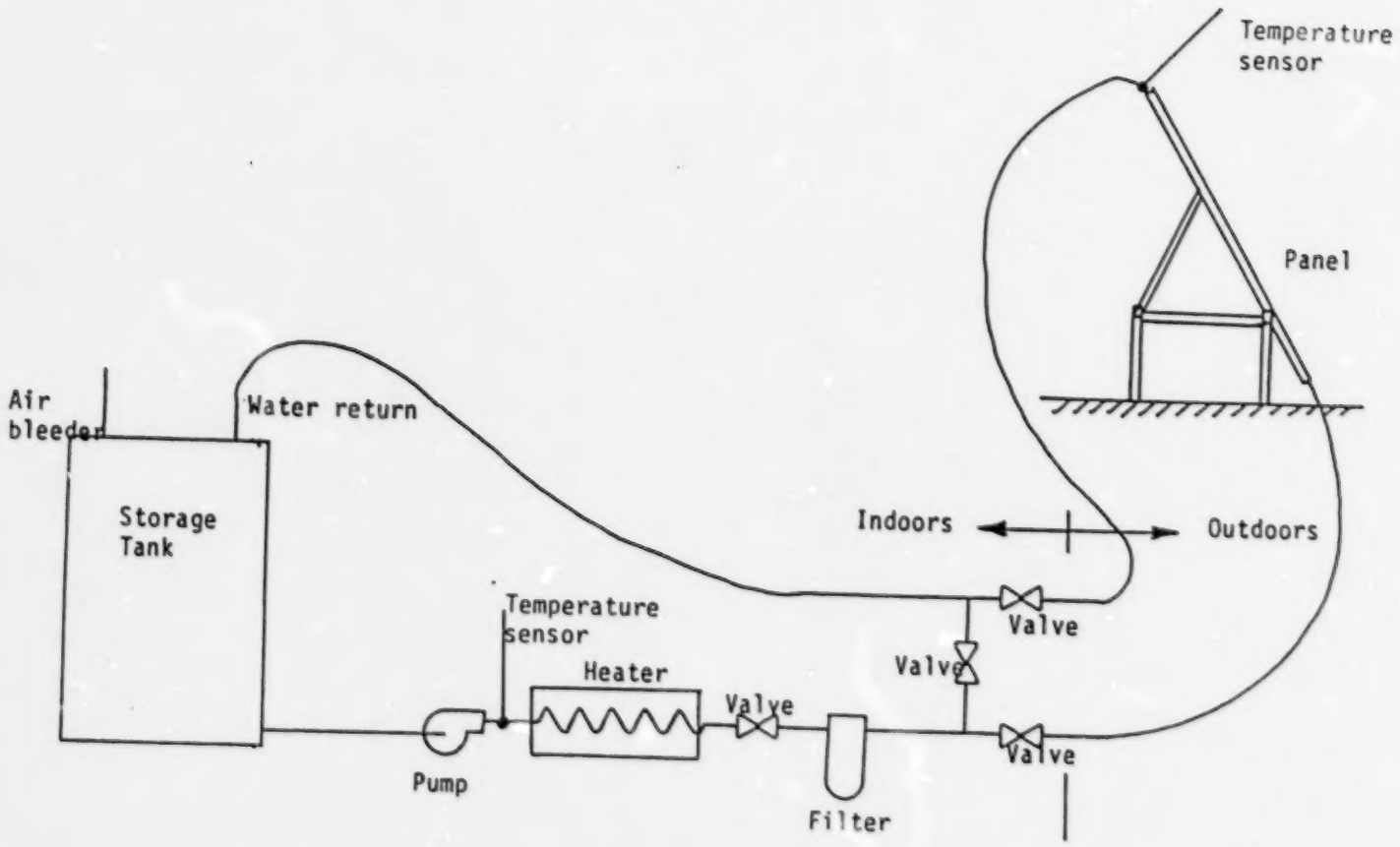

Figure 1 Setup of "Ultra-Light Solar Collector" testing facility

Readings of the pyranometer, collector intake and outlet temperatures, indoor thermocouple, outdoor thermocouple and the thermocouple mounted at the water exit from the pump were recorded every five minutes during the run.

2.2.2 Electric Heater Loop

Using the same quantity of water in the storage tank as for the collector tests, the circulating pump was switched on, and then the electric heater. The readings of the thermocouples were recorded as above, as well as the instantaneous power used by the electric heater, as measured with a wattmeter. The purpose of this part of the test was to obtain a calibration of the heat capacity of the water used in the solar collector test, since the actual amount was difficult to measure with precision.

2.3 Computations

The computations following the various tests include the evaluation of the thermal efficiency of the solar collector and the value of $\Delta T/I$, where ΔT represents the difference between the temperature of the fluid in the collector (that is, the average of the intake and oulet temperatures) and the temperature surrounding the collector during the run duration, and I is the total solar irradiation incident normal to the solar collector.

The definition used for the thermal efficiency of the solar collector is given by the ASHRAE standard 93-77 as follows:

$$\eta = \dot{m} c \delta T_c / (A_g I_T) \qquad (1)$$

where
- $\dot{m}$ = mass flow rate of fluid flowing through the collector.
- c = specific heat of the fluid flowing through the collector.
- δT_c = temperature rise of fluid across the collector
- A_g = gross area of solar collector.
- I_T = total solar intensity on the aperture plane of the collector.

The above equation requires a precise mass flow rate as well as a precise δT measurement. Both are difficult, in our case because the values are very small. An alternate approach is to consider the system efficiency by taking the ratio of energy stored to that received by the collector, in a given time period, dt. The efficiency can then be computed on the basis of the following:

$$\eta = M c \delta T_s / (A_g I_T \, dt) \qquad (2)$$

where: M = the mass of water in the system
c = the specific heat of the water in the system
δT_s = the rise in the water temperature in the storage tank during the time dt

and the other two symbols have the same meaning as before.

With this approach, considerably better precision can be achieved without excessive cost in instrumentation. The procedures used to compute the terms in this second thermal efficiency equation are given in the next few sub-sections.

2.3.1 Measurement of the Total Water Mass, M, in the System

The total mass of water in the storage tank and flow system was fixed during the test. The energy gained by the water in the tank, during a specified time, due to its passage through the solar collector, corresponds to the product of the total mass, the specific heat of the water and the rise in temperature of the water in the tank. The energy incident on the collector during this time is the product of the solar intensity on the solar collector, the area and the time.

The measurement of the total mass of water in the system was carried out by emptying the tank, from a marked level on the glass indicator on the side of the tank, into buckets and weighing the water content of the bucket. The procedure of weighing the water was repeated several times to obtain the average. The water level in the tank was maintained at this level throughout the entire investigation.

2.3.2 Measurement/Computation of the Temperature Difference of Water, δT_s

For this purpose, it was assumed that the water in the storage tank had a uniform temperature everywhere. For the flow rate used, this assumption seemed to be valid since the difference between the temperature leaving the storage tank and that leaving the collector was never more than a degree or two. These temperature readings were taken at the beginning of the test and at five minute intervals during the test period. The tank temperature was considered to be the temperature of the water in the pipe leaving the pump. The temperature rise of water in the tank over any interval of time is simply the difference between the temperatures at the beginning and end of the period.

2.3.3 Computation of the Total Normal Solar Irradiation Incident on the Solar Collector

The total radiation incident on the horizontal plane was calculated from the voltmeter reading of the pyranometer output and the pyranometer constant. It was assumed that only

the direct radiation is affected by the tilt of the collector, so that it is appropriate that these computations be performed on that portion only. Several tests were carried out to estimate the average fraction of diffuse radiation to the total radiation, by shewing the direct radiation from reading the pyranometer. These tests showed that the total radiation incident on a horizontal plane, on the days tested, was comprised of approximately 20% diffuse radiation. Therefore, the computation involving the tilt angle dealt only with 80% of the total radiation as indicated by the pyranometer. The procedure followed to compute I_T from the horizontal value I_h as measured by the pyranometer is summarized as follows (following the procedure given by Rapp[3]).

The angle of declination 'd' is calculated from:

$$\sin d = -\cos\{(Ds - 1)180°/182.6\} \sin(23.45) \qquad (3)$$

where: Ds = day of solar year (Ds = 1 on Dec 21, and Ds = 365 on Dec 20)

The hour angle 'h' is given by:

$$h = (H - 12)15° \qquad (4)$$

where: H = Local solar time
= LCT + Equation of Time

LCT = Local civil time

Equation of time is a correction because the earth's orbit is not perfectly circular. A table of the day and month and the corresponding equation of time is given by Rapp[3], which also allows for linear interpolation.

The zenith angle Θ_h (the angle between the suns rays and vertical) is calculated as follows:

$$\cos \Theta_h = \cos(L)\cos(d)\cos(h) + \sin(L)\sin(d) \qquad (5)$$

where: L = latitude (considered to be 45° for Ottawa)

Similarly the angle Θ_T (angle between the line passing through the sun and the normal to the tilted surface) is calculated from:

$$\cos \Theta_T = \cos(L-T)\cos(d)\cos(h) + \sin(L-T)\sin(d) \qquad (6)$$

where: T = tilt angle of solar collector, from the horizontal

Then the total solar intensity on a surface tilted T° toward the south is given by:

$$I_T = 0.2\ F\ I_h + 0.8\ I_h \cos(\Theta_T)/\cos(\Theta_h) \qquad (7)$$

where: I_h = total solar intensity on a horizontal surface,
F = a shape factor which accounts for the fact that a tilted collector 'sees' only a portion of the sky dome. The first term of equation (7) represents the diffuse portion and the second the direct component.

2.3.4 Computations of ΔT for the Plot η vs. $\Delta T/I$

The average temperature of water in the collector and of the ambient air over a certain period of time is estimated from the temperature measurements corresponding to this period. The value of ΔT is calculated as the difference between the two values.

3.0 Results and Discussion.

Several tests were carried out for two tilt angles of the solar collector; namely at 60° and 78°. The variation in the test conditions in each case was limited only to the initial temperature of water in the storage tank. The results from the tests at a 60° tilt angle are plotted in Figure 2 with $\Delta T/I_T$ as the abscissa and η as the ordinate.

The results for the two tilt angles were essentially the same, when correction for the solar energy intercepted is made. Operating at the higher tilt angle results in less energy intercepted, however, and therefore less collected. Nevertheless, this is a very encouraging result since one of the objectives of this study was to examine the possibility of vertical mounting of the ultra light-weight flat plate solar collector. This seems to be very feasible as the degradation in thermal efficiency is caused only by the lower effective area intercepting the solar radiation at the higher tilt angle.

A series of tests was performed to evaluate the heat losses from the pipes connecting the storage tank to the collector, since the technique used for measurement included these losses as though they reduced the collector efficiency, or, in other words, to convert from an effective system efficiency to a collector efficiency. For this purpose, the pipes were run outside for the same length as though they were connected to the collector, but they by-passed the collector. The reduction of temperature of the water in the tank was now monitored. Based on these measured losses, the measurements made with the collector were corrected.

The thermal performance is considered to be quite acceptable, considering the simplicity of the collector. The absorber did not fully utilize the space within the frame, with at least an inch (2.5 cm.) clearance between the outer edge of the outside fins and the frame. Therefore, the performance based on the outside area of the collector, as this was, could immediately be improveded by at least 4% by bringing the frame in that extra amount. This is being given careful consideration in the design review that is ongoing.

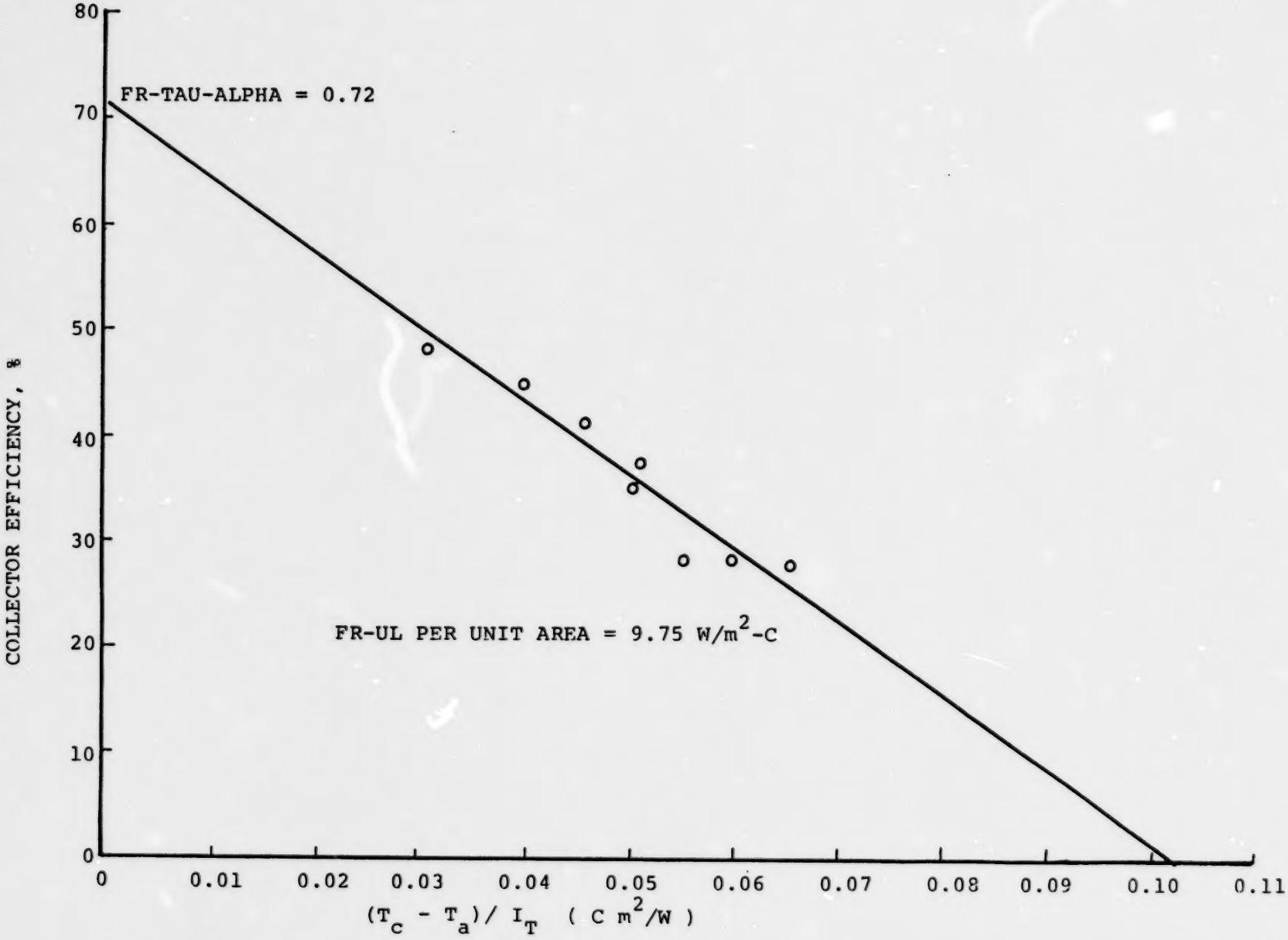

Figure 2 Measured thermal efficiencies for the ultra light-weight collector, showing least-squares fit line passing through the points, for 60 degree tilt angle.

4.0 Evaluation of the Flexural Rigidity of the Solar Collector

A desireable feature of a solar collector is that it can be mounted on a roof and bear the loads to which a roof is subjected. If the collector cannot bear the required loads, it can be destroyed in the testing process. Since we did not want that to happen, our approach was to determine a measure of the stiffness of the collector, without testing the unit to failure. Our approach was to obtain an effective product of the moment of inertia of the section, I, and the elastic modulus, E. This product, EI, called the flexural rigidity of the section, allows the computation to be made of the deflection of the collector with various loads.

Testing to determine the effective flexural rigidity was done by supporting the collector in a horizontal plane, with the support across the entire width of the section at two points, in effect treating the collector as a beam. The deflection was then measured for the various load distributions. The load consisted of plastic bottles filled with water, each of ~4.5 kg weight, distributed in several different patterns in the various tests.

The weights were added one at a time, placing them in pairs symmetrically about the axis of symetry of the collector and the deflection was measured at the centre of the two sides of the collector. The deflection was considered to be the average of the two readings. Figure 3 shows the first set-up used to evaluate the flexural rigidity of the ultra lightweight flat plate solar collector simply supported near the edges. Figure 4 shows the arrangement during a clamped support of the collector at four points, (two on each side of the collector). The product EI was calculated for both cases following the procedure outlined by Singer[4].

The value of EI at maximum load of ~ 50kg when simply supported was 17,255 Nm^2. The value of EI corresponding to the clamped support was ~3,600 Nm^2 at a load of ~ 100 kg. The maximum deflection measured at the centre of the collector in the first case was ~8 mm whereas it was ~2 mm using the second method of support. Clearly the flexural rigidity does not change with the method of support, so we would have to conclude that the larger number is the actual effective value, and that the 'beam' was not truly clamped in the second case.

The stiffness of the collector may be increased if some stiffening strips were applied, during manufacturing, between the facing sides, and if the back glazing (which is not really needed) was replaced by a sheet of thin aluminum riveted to the frame. Alternately, if the back and sides were made of one integral piece, the overall stiffness would be increased. Provision of some brackets near the corners of the frame would also increase the stiffness of the collector.

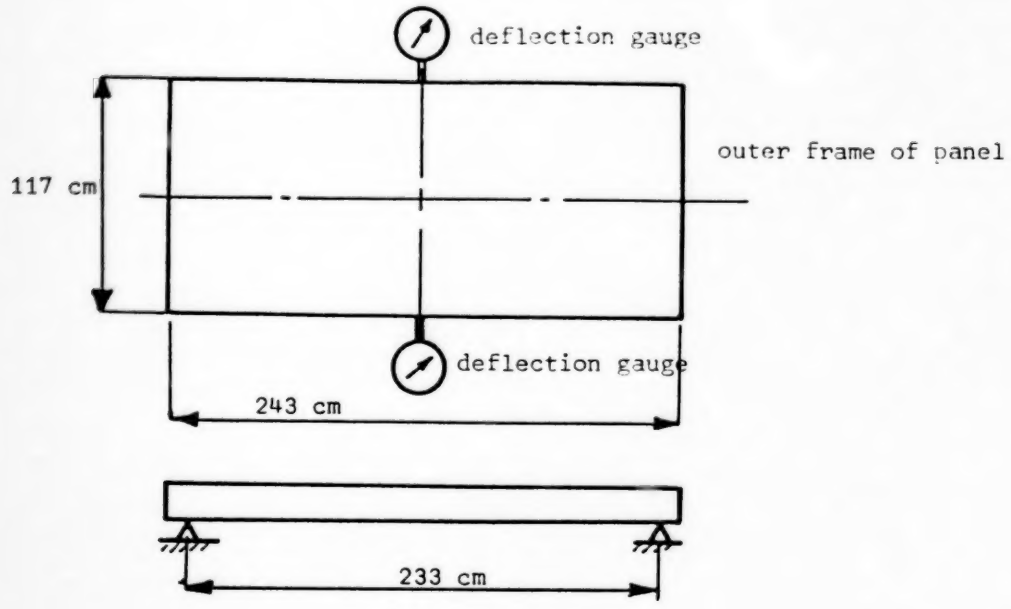

Figure 3 Schematic diagram of the simply supported collector and the location of the deflection gauges

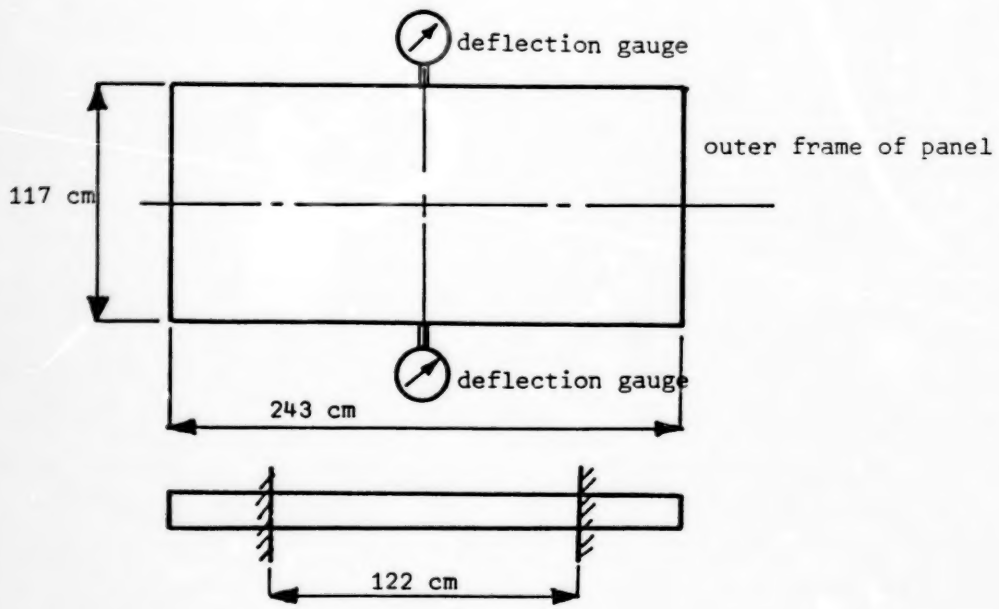

Figure 4 Schematic diagram of the collector fixed along two lines and the location of the deflection gauges

5.0 Possible Design Changes

This section presents a summary of suggestions regarding modifications of design and set up to improve the thermal performance and strength of the ultra light-weight flat plate solar collector. These suggestions are based on results of experimental tests conducted over the course of this study. The suggestions are made, as well, with the consideration of further reducing the cost of manufacturing of the collectors.

5.1 Changes Related to Thermal Performance

a. If the original concept of the thin film absorber could be combined with the roll-bonded approach used on the 'Sunstrip' fins, it may be possible to use a single sheet rather than multiple fins. Some improvement in the thermal performance may result from this change, but primarily improved efficiency in manufacturing and improved strength of the section are expected.

b. Another alternative would be to use the 'Sunstrip' concept, but use narrower fins so that the fin length is less. This should result in more efficient transmission of the energy collected to the fluid channel, thereby improving the overall thermal efficiency of the collector unit, but it would also increase the cost.

c. Since the overall performance is related to the gross area of the collector and not the absorber area, reduction of the space around the absorber which adds to the gross area but which does not contribute to the energy collected should be eliminated as much as possible.

d. The pipes and hoses connecting the various components of the set-up should be made as short as possible and well insulated to reduce the heat losses from these surfaces and thereby assist in retaining the energy collected by the solar collector.

e. Lower speeds of the pump should be investigated to determine the thermal efficiency under these speeds.

f. If an improved glazing could be obtained which had greater scratch resistance, this could give longer term good performance.

g. The insulation of the back of the absorber could be improved if polyisocyanurate was used in double thickness rather than using a layer of fiberglass. The fiberglass was used to give high temperature protection in the case of stagnation. It is noted, however, that other manufacturers have collectors on the market which have only polyisocyanurate insulation. Therefore it is quite likely that the fiberglass is not essential.

5.2 Changes Related to Strength

a. The back glazing should be replaced by a thin aluminum sheet riveted to the frame. This should enhance the rigidity of the collector structure considerably as well as reduce the material cost.

b. An alternative to riveting the back to the sides is to make the back and sides of one integral sheet of metal, thereby further increasing the strength. This is being examined in some detail in the ongoing design review of this collector.

c. Brackets should be used at the frame corners to enhance the rigidity.

d. Small strips of aluminum should be added to join the two opposite sides of the collector at various locations along the sides. This may not affect the strength greatly if the back is covered with a sheet of aluminum.

5.3 Changes Related to Cost

a. Replacing of the back glazing, as mentioned earlier, will reduce the material costs, at least on the basis of purchase of small quantities, and may not add substantially to the labour costs.

b. As suggested earlier, making the absorber with two sheets of aluminum roll-bonded at the edges, as well as at the ends, to provide good seals all around, and with a lighter weight material would reduce the material costs. The development cost would increase, however.

6.0 Marketing Appraisal

The market potential of a solar collector is determined by its thermal performance to cost ratio, provided it has adequate strength, reliability and longevity to meet the application requirements. Only a part of these conditions can be addressed on the basis of the work that has been done with our light-weight flat plate collector, to date. In this section, a summary is given of the points that will affect its marketability, and then a few comments are added regarding the possible potential on the basis of these numbers.

6.1 Performance

The performance is determined by simulation runs on a computer using the WATSUN software. The simulation input data and performance summary are included in Appendix A. With the slightly rather larger FR-UL (which indicates the heat loss from the collector), than had been hoped for,[5] the performance was not quite as good as had been hoped. Even with this performance, because of the low cost of the collector units, the energy they supply would be cost competitive with electrical costs of under 5 cents per kW-hr. Locally, the electrical costs are in that vicinity so the collector could begin to penetrate the local market, with an appropriate marketing strategy. In parts of the U.S.A. and in the south sea islands, the electrical costs are more than double this rate, so the collector would appear to be very attractive in such areas. In more southerly type climates, the larger value of FR-UL would not be as large a penalty either, so the market for these collectors is expected to be very good in such areas.

The salvage value at the end of the ten year system life is based largely on the continued value of the non-collector components. With respect to the collector itself, even if the glazing needs to be changed more often than one made of glass, the other parts would have a longevity similar to that of a more conventional heavy collector.

It should be noted that with the large number of input variables to the simulation, many possible combinations can be envisioned, and each design would result in some differences. In the simulations run, it was noted that the solar energy unit cost increased as the number of collector units increased, when everything else remained the same. This is expected since the larger number of collectors supply a larger fraction of the required energy to be used, and therfore, on average, supply energy at a higher temperature. This in turn results in lower thermal performance, and therefore lower return on investment. To be fair, the storage volume should also increase in proportion to the collector area in order for the simulation to be more realistic.

An approximate simulation of a 3-collector module swimming pool solar heater was run with the Watsun program by assuming a very large storage tank which had little losses and did not cost extra (we did not have the WATSUN swimming pool module). A small allowance was made for piping and a stand for the collectors. On this basis the simulation showed that the energy collected cost about $4./GJ, which is less than 30% the cost of heating with local electrical power. Therefore, on economic grounds, it would seem that the Asecor ultra-light weight collector could be a popular swimming pool heater in Canada, and that it could also do very well as a domestic water heater in warmer climates.

6.2 Cost

Table 1 gives a cost breakdown of the various parts of the 4' x 8' collector, first as experienced in making the prototype, and then secondly as we expect to achieve when making more than just the occasional one for the solar market. It indicates that a price of $100./$m^2$ is an achievable target.

The ability of this collector to be mounted vertically (or near vertical) should prove to be an important asset where land prices are high or space is unavailable for sloping installations. For example, the side walls, (and roof) if they can withstand the load of the collectors, of a building can be covered by solar collectors. The light weight feature of this collector facilitates roof top mounting, without the weight penalty of other collectors.

6.2 Market Potential

As indicated in section 6.1, this collector is best suited for relatively low temperature applications, such as swimming pools, or domestic hot water preheat or possibly in some industries using large amounts of warm water, especially in the summer.

The new housing starts for Canada are expected to be in the range of 120,000 to 160,000 per year over the next 15 years[6], with 165,826 starts in 1986.[7] If one percent of these opt for a solar domestic hot water system, and if the Asecor system supplies ten percent of these, this would amount to 120 to 160 systems per year. Taking only the collector portion of that system, with three collector units per system, this represents a gross revenue of 108,000 to 144,000 per year.

As of May 1986, 5,849,000 homes in Canada had a total of 436,000 swimming pools.[7] If Asecor can sell 3-collector unit pool heaters to 0.1% of these per year, this would represent a gross revenue of $392,400. per year.

Finally, Asecor is in the process of making contacts with a group in the West Indies, which could be the beginning of

solar sales in that part of the world. In total, there is a large potential out there which needs to be tapped. Good sales technique and aggressiveness will be needed to realize the share suggested above.

Table 1: Cost Estimate for Ultra-Light Weight Flat Plate Solar Collectors

COMPONENT	4' x 8' SUNSTRIP PROTOTYPE CURRENT PRICES	TARGET PRICES
Aluminum frame 5052 H-34 0.020"	$15.66	$12.00
forming of frame	9.00	6.00
Absorber: Sunstrip 10-0.03" x 4.5" x 90" with 1" headers	113.66	100.00
Selective Surface: Black nickel α = 0.95 ε = 0.15	included with absorber price	---
Insulation: Thermax polyisocyanurate 1' x 48" x 96"	28.62	18.00
Fiberglass 1" x 24" x 48"	14.00	5.00
Glazing: Tedlar 2-4 mil x 48" x 100"	89.56	50.00
Adhesive: 3M isotac 1" x 60 yds./roll	5.25	3.50
Miscellaneous: Mounting brackets, grommets, rivets, etc.	10.00	5.00
TOTAL COST PER COLLECTOR	$285.75	$199.50
AREA PER COLLECTOR - m^2	2.97	2.97
UNIT COST - $/$m^2$	$96.12	$67.17
Expected Labour cost/collector		$50.00
Mark-up to cover overhead and profit		50.00
Total wholesale selling price per 4' x 8' collector		$299.50
Wholesale selling price per m^2		$100.84

7.0 Summary and Recommendations

7.1 Summary

The thermal performance and strength of the "Ultra Light-Weight Flat Plate Solar Collector" has been experimentally evaluated. The thermal efficiency of the collector was found to be greater than 50% for temperature differentials of less than 27°C, dropping to ~20% for temperature differentials in the vicinity of 70°C. The tilt angle of the collector was adjusted up to 78° and operation with larger angles is possible, such as with vertical mounting. The system thermal efficiency could be improved noticeably if the pipes connecting the various parts of the arrangement are insulated to reduce heat losses. Attaching an aluminum sheet as the back of the collector could reduce the cost and add to the strength.

7.2 Recommendations

The following suggestions are offered for future considerations in the on-going improvement of the ultra light-weight flat plate solar collector. They are divided into three categories.

7.2.1 Thermal Performance Characterization

Within the limited resources allocated to this project, there was not sufficient opportunity to iterate between evaluation, change and re-evaluation. Although the project discussed in this report is ended, the design is continuing to be improved, with a re-designed means of attaching the Tedlar glazing being implemented, and an improved container for the absorber being built to improve its rigidity. The previous work[1] involved consideration of many alternatives for the absorber, so no new attempts were made in this project to introduce other concepts for this component. Further work of this nature is recommended. Performance tests over a wider range of weather conditions (i.e., outdoor temperatures) would be useful to establish the performance numbers more fully. Stagnation tests should also be done, as well as summer-time testing as it applies to pool heating applications.

Improvement in the system performance could be realized if the pipes leading to the collector were insulated. This was not done in the tests reported, since it was intended that these losses could be calibrated. In retrospect, it would have been better to insulate the pipes.

One alteration that appears worth pursuing is that of using narrower fins of the type used here. This should result in better fin efficiency and correspondingly better performance, but with increased costs which should be investigated. Elimination of the space around the outer fins would reduce the gross area and increase the performance figures.

7.2.2 Strength Considerations

Although the flexural rigidity was obtained from experiments, the ultimate strength is not known. It would be useful to have this information for the purpose of designing the appropriate support for the collector. Some additional strength could be realized by using an aluminum sheet on the back surface of the collector in place of the plastic film used in the present prototype. The strength of the outer frame was not what it would have been if we could have had it made according to our original design.[1] Since none of the local machine shops could make it that way, we settled on the present design. If production quantities were manufactured, it would be worthwhile acquiring the equipment to make the frame as it was intended.

As noted in the previous section, an alternate design for the container is being considered, which would possibly increase the overall rigidity as well as reduce the required labour content in assembling the collector units.

7.2.3 System Assembly and Characterization

The simulations summarized in Appendix A are based on expectations and some guesses as to an appropriate system assembly. More attention should be given to assembling a system (or systems) which is (are) optimized for this collector, based on its best performance scenario. A pool heating system would be of considerable interest if it could supply energy at the effective price of $4./GJ as suggested by the approximate simulation. Domestic water heaters would also be of interest, especially for cottages, or for regions with high electricity prices. Actual assembly and testing over an extended period of time would be beneficial to further marketing of the product.

APPENDIX A

WATSUN Simulation Input Data and Results

A-1. Solar Domestic Hot Water (WATSUN) Simulation Input

Three simulations are reported, with 1, 2 and 3 collector units in a domestic hot water system. The input file is the same for each except for the collector area. The output file shows the resulting performance differences expected in A-2.

a) Collector Data

1.	Collector Area (m^2)		2.97, 5.94, 8.91
2.	Maximum Collector Outlet Temperature (C)		98.00
3.	Differential Temperature for Control (C)		1.00
4.	Pump Power in Collector Loop per Area (W/m^2)		0.00
5.	Thermal Capacitance Flow Rate/Area (W/m^2-C)		50.00
6.	Fr-Tau-Alpha Product		0.72
7.	Fr-Ul per unit area (W/m^2-C)		9.75
8.	Collector Slope (degrees)		60.00
9.	Collector Azimuth (0=South)		0.00
10.	Allow Pipe Losses (No=0.0)		0.00
11.	Incident Angle Modifier:	Angle 0.00	1.00
		30.00	1.00
		45.00	0.97
		60.00	0.88
		90.00	0.00

b) Storage Tank Data

1.	Preheat Tank Volume (m^3)	1.00
2.	Wall Area Including Top (m^2)	5.00
3.	Floor Area (m^2)	1.00
4.	Heat Loss Factor (W/m^2-C)	0.50
5.	Density * Heat Capacity of Fluid (kJ/m^3-C)	4200.00
6.	Starting Preheat Tank Temperature (C)	20.00
7.	Maximum Temperature in Preheat Tank (C)	98.00
8.	Auxiliary Tank Volume (m^3)	1.00
9.	Wall Area Including Top (m^2)	3.21
10.	Floor Area (m^2)	0.29
11.	Heat Loss Factor (W/m^2-C)	0.80
12.	Density * Heat Capacity of Fluid (kJ/m^3-C)	4200.00
13.	Maximum Temperature in Auxiliary Tank (C)	98.00
14.	Basement Temperature (C)	20.00
15.	Basement Floor Temperature (C)	18.00

c) Domestic Hot Water Load Data

1.	Minimum Water Mains Temperature (C)	10.00
2.	Maximum Water Mains temperature (C)	18.00
3.	Desired Hot Water Set Temperature (C)	55.00
4.	Type of Load (1 = Volumetric)	1.00
5.	Load Specification (0 = Annual)	0.00

A-1: Solar Domestic Hot Water (WATSUN) Simulation Input (Continued)

d) Daily Hot Water Loads

1.	Total Daily Load (L/day)	175.00

2. Hourly Load Schedule (%)

1: 2.25	2: 0.00	3: 0.00	4: 0.00	5: 0.00
6: 0.00	7: 1.50	8: 4.65	9: 7.25	10: 8.49
11: 6.90	12: 4.50	13: 3.60	14: 5.10	15: 2.70
16: 2.40	17: 2.10	18: 3.75	19: 6.75	20: 11.60
21: 9.60	22: 6.90	23: 5.46	24: 4.65	

e) Exchanger Data

1.	Collector/Storage Exchanger Type	External
2.	Exchanger Parameter 1	1.00
3.	Exchanger Parameter 2	0.00
4.	Storage/Load Exchanger Type	External
5.	Exchanger Parameter 1	1.00
6.	Exchanger Parameter 2	0.00
7.	Thermal Capacitance Flow Rate (W/C)	0.00

f) Economic Data

1.	System Life (Years)	10.00
2.	Term of Loan (Years)	10.00
3.	Interest Rate on Loan as a Fraction	0.10
4.	Rate of Return (Discount Rate as a Fraction)	0.10
5.	Cost of Collector per unit Area ($/m^2)	100.00
6.	Cost of Storage per unit Volume ($/GJ)	100.00
7.	Cost of Auxiliary Energy per GJ ($/GJ)	13.88
8.	Other Fixed Costs ($)	50.00
9.	Salvage Value At End of System Life ($)	150.00
10.	Yearly Maintenance Cost ($/Year)	20.00
11.	Yearly Fuel Price Escalation For Life (%)	

1: 0.00	2: 13.00	3: 13.00	4: 10.00	5: 10.00
6: 10.00	7: 10.00	8: 7.00	9: 7.00	10: 7.00

g) Other Data

1. Weather Data: For Ottawa, Ont.
   Latitude 45.45° N.

A-2: Energy Analysis Summary

Explanation of Column Headings Used:

1. HTOT = Total Radiation (GJ) falling on the Collector
2. QCOL = Energy Collected (GJ)
3. QDHW = Demand for Hot Water (GJ)
4. QSHW = Energy From Storage to DHW (GJ)
5. AUXW = Auxiliary Energy for Water Heating (GJ)
6. QTLS = Total Losses From Tanks (GJ)
7. M = Month of Simulation

a) Collector Area: 2.97 m^2

M	HTOT (GJ)	QCOL (GJ)	QDHW (GJ)	QSHW (GJ)	AUXW (GJ)	QTLS (GJ)
1	0.97	0.24	1.26	0.21	1.05	0.27
2	1.49	0.35	1.16	0.31	0.85	0.28
3	1.66	0.46	1.28	0.39	0.90	0.32
4	1.51	0.50	1.22	0.41	0.81	0.33
5	1.55	0.52	1.22	0.44	0.78	0.36
6	1.40	0.52	1.14	0.40	0.74	0.36
7	1.54	0.59	1.13	0.43	0.70	0.39
8	1.55	0.58	1.11	0.45	0.66	0.41
9	1.37	0.49	1.07	0.37	0.70	0.37
10	1.14	0.38	1.13	0.32	0.81	0.35
11	0.77	0.25	1.14	0.24	0.90	0.30
12	0.78	0.18	1.22	0.17	1.05	0.27
==	====	====	====	====	====	====
YR	15.74	5.06	14.09	4.14	9.95	4.02

b) Collector Area: 5.94 m^2

M	HTOT (GJ)	QCOL (GJ)	QDHW (GJ)	QSHW (GJ)	AUXW (GJ)	QTLS (GJ)
1	1.95	0.39	1.26	0.31	0.95	0.30
2	2.99	0.54	1.16	0.45	0.71	0.33
3	3.31	0.70	1.28	0.56	0.72	0.38
4	3.01	0.74	1.22	0.58	0.64	0.39
5	3.11	0.74	1.22	0.62	0.60	0.43
6	2.79	0.74	1.14	0.56	0.58	0.41
7	3.08	0.85	1.13	0.60	0.53	0.45
8	3.11	0.82	1.11	0.63	0.48	0.47
9	2.74	0.73	1.07	0.55	0.53	0.43
10	2.28	0.57	1.13	0.47	0.66	0.41
11	1.55	0.40	1.14	0.36	0.78	0.34
12	1.56	0.30	1.22	0.25	0.97	0.30
==	====	====	====	====	====	====
YR	31.48	7.50	14.09	5.94	8.16	4.65

A-2: Energy Analysis Summary (continued)

c) Collector Area: 8.91 m^2

M	HTOT (GJ)	QCOL (GJ)	QDHW (GJ)	QSHW (GJ)	AUXW (GJ)	QTLS (GJ)
1	2.92	0.51	1.26	0.38	0.88	0.33
2	4.48	0.66	1.16	0.54	0.62	0.36
3	4.97	0.85	1.28	0.67	0.61	0.42
4	4.52	0.89	1.22	0.69	0.53	0.43
5	4.66	0.87	1.22	0.72	0.50	0.46
6	4.19	0.87	1.14	0.66	0.48	0.45
7	4.62	1.00	1.13	0.71	0.43	0.49
8	4.66	0.97	1.11	0.74	0.37	0.51
9	4.12	0.87	1.07	0.66	0.42	0.47
10	3.42	0.69	1.13	0.57	0.56	0.44
11	2.32	0.50	1.14	0.44	0.70	0.37
12	2.34	0.39	1.22	0.32	0.90	0.32
==	====	====	====	====	====	====
YR	47.22	9.07	14.09	7.09	7.00	5.06

A-3: Simulation Output - Efficiency

Table Headings and Their Meanings:
1. COL.EFF = Collector Efficiency = QCOL/HTOT
2. STO.EFF = Storage Efficiency = QSHW/QCOL
3. SYS.EFF = System Efficiency = QSHW/HTOT
4. PREHEAT LOSS = Percent Tank Loss - Preheat = QPTL/QTLS
5. SOLAR FRAC. = Solar Fraction = QSHW/QDHW

a) Collector Area: 2.97 m^2 Storage Vol. 1.0 m^3

M	COL. EFF. (%)	STO. EFF. (%)	SYS. EFF. (%)	PREHEAT LOSS (%)	SOLAR FRAC. (%)
1	24.18	90.75	21.95	2.36	16.94
2	23.65	87.66	20.73	14.27	26.68
3	27.98	83.71	23.42	18.49	30.23
4	33.13	82.13	27.21	23.36	33.57
5	33.46	84.32	28.22	27.51	35.90
6	37.04	76.94	28.50	28.79	35.02
7	38.61	72.21	27.88	32.50	37.86
8	37.13	77.83	28.90	35.13	40.46
9	35.69	76.35	27.25	31.36	34.79
10	33.12	84.74	28.07	25.28	28.22
11	32.43	95.99	31.13	15.92	21.18
12	23.02	94.92	21.85	2.09	13.97
YR	32.13	81.88	26.31	22.79	29.38

Percent Energy Saved: 29.38
Present Worth (Operating Energy Included) = $ 1806.
P.W. (Operating Energy Not Included) = 512.
Life-Cycle Unit Cost ($/GJ) = 12.81
Solar Life-Cycle Unit Cost ($/GJ) = 12.36

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b) Collector Area: 5.94 m^2 Storage Vol. 1.0 m^3

M	COL. EFF. (%)	STO. EFF. (%)	SYS. EFF. (%)	PREHEAT LOSS (%)	SOLAR FRAC. (%)
1	20.14	78.78	15.86	13.05	24.49
2	18.03	83.28	15.01	27.06	38.63
3	21.14	79.88	16.89	31.28	43.59
4	24.58	78.75	19.36	35.19	47.77
5	23.80	83.33	19.83	38.16	50.46
6	26.49	75.53	20.01	38.48	49.18
7	27.50	71.36	19.62	41.65	53.28
8	26.38	76.85	20.27	43.91	56.77
9	26.43	75.45	19.94	41.01	50.91
10	24.80	83.32	20.66	35.08	41.56
11	25.59	90.11	23.06	25.89	31.38
12	19.08	85.43	16.30	11.74	20.84
YR	23.83	79.17	18.87	33.26	42.13

Percent Energy Saved: 42.13
Present Worth (Operating Energy Included) = $ 1870.
P.W. (Operating Energy Not Included) = 810.
Life-Cycle Unit Cost ($/GJ) = 13.26
Solar Life-Cycle Unit Cost ($/GJ) = 13.62

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c) Collector Area: 8.91 m^2 Storage Vol. 1.0 m^3

M	COL. EFF. (%)	STO. EFF. (%)	SYS. EFF. (%)	PREHEAT LOSS (%)	SOLAR FRAC. (%)
1	17.47	74.88	13.08	19.81	30.30
2	14.69	81.87	12.03	33.53	46.42
3	17.16	78.70	13.50	37.65	52.28
4	19.78	77.40	15.31	40.91	56.67
5	18.71	83.09	15.55	43.24	59.33
6	20.87	75.14	15.68	43.19	57.81
7	21.56	71.03	15.31	45.96	62.37
8	20.71	76.25	15.79	48.02	66.33
9	21.18	75.19	15.93	45.78	61.00
10	20.24	82.62	16.72	40.30	50.45
11	21.46	87.88	18.86	31.54	38.48
12	16.46	82.38	13.56	17.83	26.00
YR	19.21	78.19	15.02	38.60	50.31

Percent Energy Saved: 50.31
Present Worth (Operating Energy Included) = $ 2016.
P.W. (Operating Energy Not Included) = 1106.
Life-Cycle Unit Cost ($/GJ) = 14.31
Solar Life-Cycle Unit Cost ($/GJ) = 15.60

It should be noted that 5 cents/kW-Hr corresponds to 13.88 $/GJ

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